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A HIGH-RESOLUTION STUDY OF THE ISOTOPES OF SOLAR FLARE NUCLEI

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ABSTRACT

Individual isotopes of the elements He, C, N, O, Ne, and Mg with energies from ~5 to ~50 MeV per nucleon have been resolved in energetic solar flare particles during the 1978 September 23 solar flare event. These C, N, and O measurements are the first solar flare isotope measurements reported for these elements. In addition, we have improved on our earlier determination of $^{22}Ne/^{20}Ne$ in this flare by extending the energy interval for isotope analysis. We continue to find a significant difference between the isotopic composition of solar flare and solar wind neon, which we compare to similar evidence from studies of solar energetic particles implanted in lunar and meteoritic samples. Although limited by statistics, our measurements of He, C, N, O, and Mg isotopes are consistent with typical isotopic abundances found in other samples of solar system material. The ensemble of these results is used to test for the possibility of mass-dependent fractionation during solar flare acceleration and propagation. Finally, measurements of the elemental composition and energy spectra of this event allow us to interpret our isotope measurements within a broader context of solar flare composition studies.

Subject headings: cosmic rays: abundances — Sun: abundances — Sun: flares

I. INTRODUCTION

Knowledge of the isotopic composition of solar system material is essential to studies of the origin of the elements in stars and studies of the formation of the solar system. Although the Sun is the major reservoir of solar system material, most of our present knowledge of the solar system isotope distribution comes from studies of terrestrial, lunar, and meteoritic material. During the past few years, interest in the solar isotopic composition has been intensified by the discovery of a host of isotopic anomalies in meteorites, which show that the solar system was not homogeneous when formed. Satellite-borne spectrometers which measure solar energetic particles (SEPs) now provide a new means of sampling directly the composition of solar material.

Neon was the first element heavier than helium for which solar flare isotope measurements were reported. These results were especially interesting in that both the *IMP 8* results from the University of Chicago, which were summed over seven flares (Dietrich and Simpson 1979), and our *ISEE 3* measurement in the 1978 September 23 solar event (Mewaldt *et al.* 1979), found the SEP $^{22}Ne/^{20}Ne$ ratio to be considerably greater than that measured in the solar wind (SW) on the *Apollo* missions (Geiss *et al.* 1972). This difference suggested the possibility of mass fractionation in either the SW or the SEP acceleration or propagation processes. However, SEP measurements of the $^{25}Mg/^{24}Mg$ and $^{26}Mg/^{24}Mg$ ratios in the 1978 September 23 event were found to be consistent with measured terrestrial and meteoritic abundances for these isotopes (Mewaldt *et al.* 1981*a*; see also Dietrich and Simpson [1981] for $^{26}Mg/^{24}Mg$).

In this paper we report new analyses of He, C, N, O, Ne, and Mg isotopes observed during the 1978 September 23 solar flare, which we compare with other measurements of solar system isotopes. Preliminary versions of some of this work have been reported elsewhere (Mewaldt *et al.* 1981*b*; Mewaldt, Spalding, and Stone 1983), and further details can be found in Spalding (1982).

II. INSTRUMENTATION AND DATA ANALYSIS

The Caltech Heavy Isotope Spectrometer Telescope (HIST) is carried on the *ISEE 3* spacecraft, launched 1978 August 12 into a heliocentric orbit approximately 0.01 AU sunward of Earth. HIST was designed to measure the isotopic composition of solar and galactic cosmic ray nuclei from Li to Ni in the energy range from ~5 to ~250 MeV per nucleon. The instrument operated normally for a period of 110 days until a component in the HIST readout logic failed on 1978 December 1 reducing the number of data bits transmitted to Earth, and limiting the period during which high-resolution data, such as those reported here, could be accumulated.

The HIST telescope, shown schematically in Figure 1, consists of an array of silicon solid-state detectors of graduated thicknesses labeled M1, M2, and D1 through D9. An important refinement over earlier experiments is the use of two-dimensional position-sensitive detectors M1 and M2, which allow the determination of individual particle trajectories. M1 and M2 are 50 μm thick surface-barrier devices with a matrix of strips at 1 mm intervals forming an X-Y hodoscope. Use of this trajectory information results in a significant improvement in mass resolution compared with telescopes with similar opening angles that do not have trajectory measuring capability. In addition, the signals from both M1 and M2 are analyzed to provide energy-loss information.

Detectors D1, D2, and D3 are conventional surface-barrier detectors, while D4 to D9 are double-grooved Li-drifted detectors with a central area for measuring energy loss, and an annular guard (G) used as an anticoincidence shield. For convenience, we label the "range" of particles stopping in HIST by the identity of the last detector triggered. The present study includes particles stopping in M2 to D4 (range 0 to range 4 events). Further details of the design and operation of HIST are given in Althouse *et al.* (1978).

Resolution of isotopes in HIST is accomplished by a refinement of the standard dE/dx total-energy technique. As shown in Mewaldt *et al.* (1979), for each stopping particle that triggers

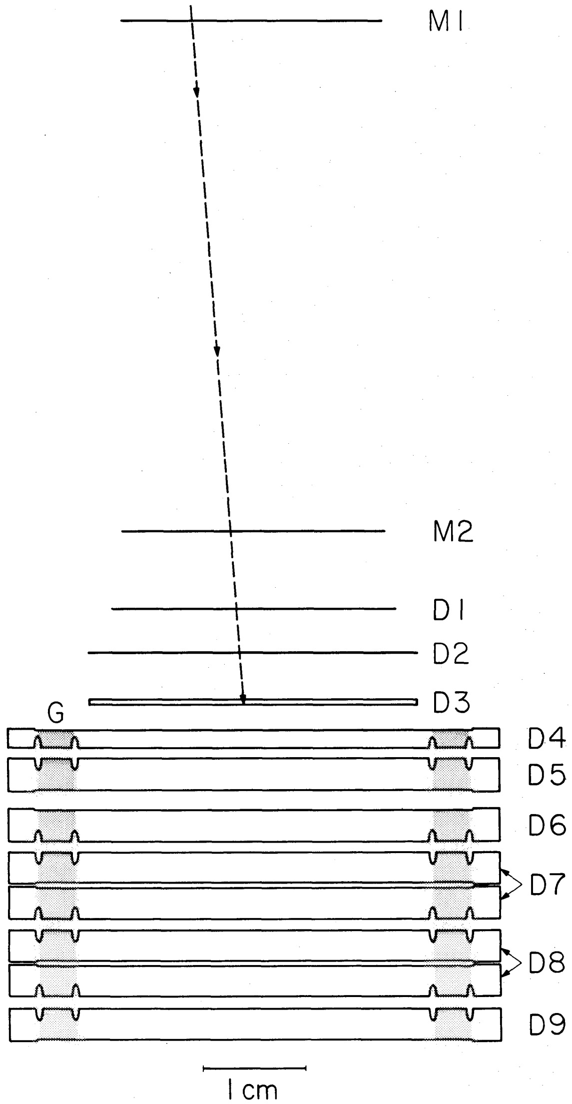

FIG. 1.—Schematic of the HIST sensor. M1, M2, and D1 through D9 are silicon solid-state detectors. The trajectory of a typical range 3 event is indicated.

N detectors it is possible to make $N-1$ essentially independent determinations of the particle's nuclear charge (Z) and its mass (M) by taking appropriate combinations of detectors to determine the energy loss ΔE and the residual energy loss E'. Intercomparison of these determinations is a powerful technique for identifying and eliminating background events. This study typically used three such charge and mass estimates for range 2 and range 4 events, and two estimates for the other ranges. Those events for which these individual mass estimates were consistent (typically to an accuracy of $\sim 6\%$; see Spalding 1982) were selected for further analysis. For each of these events, a best estimate of the mass was obtained from a weighted average of the individual estimates.

III. OBSERVATIONS

The observations reported here were made during the large solar particle event of 1978 September 23, which was detected by HIST and by ground-level neutron monitors within one hour after the observation of a 2B Hα solar flare at 35 N, 50 W (*Solar Geophysical Bulletin*, 1978 October, November). The isotope data included in this study were obtained from 10:00 UT on 23 September 1978 to 23:59 UT on September 27, during which time the counting rate of $Z > 2$ nuclei in HIST ranged from $\sim 10^2$ to $> 10^4$ times its nominal quiet-time level. Although HIST also observed other solar events during its period of nominal operation, the intensity of $Z > 2$ nuclei in these smaller events was only a few percent of that in the 1978 September 23 flare.

Figure 2 shows the mass histograms obtained for He, C, N, and O nuclei, where the observed rms mass resolution ranges from 0.13 to 0.23 amu. Note the well-resolved peak due to ^{13}C and the small clump of events at ^{18}O. This is the first time that these two rare isotopes have been resolved in measurements of solar energetic particles.

Figure 3 shows mass histograms for Ne in two energy intervals and Mg data reported earlier (Mewaldt *et al.* 1981*a*). Our earlier Ne measurement (Mewaldt *et al.* 1979) was based on range 2 and range 3 data. The bulk of our new data is at lower energy (range 1) where the two position-sensitive detectors (M1 and M2) are used as ΔE devices. We have also added seven events at higher energy (range 4), and in addition, 22 events from ranges 2 and 3, obtained by relaxing some-

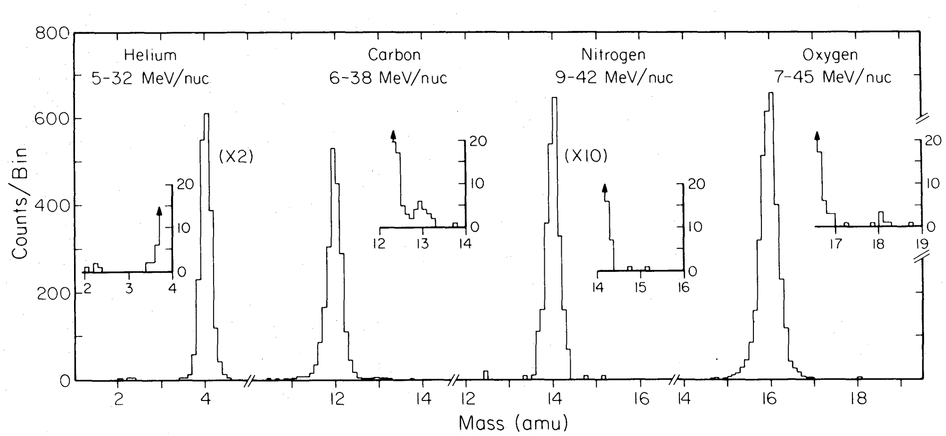

FIG. 2.—Mass histograms of solar flare He, C, N, and O nuclei in the indicated energy intervals. The insets show the ^{3}He, ^{13}C, ^{15}N, and ^{17,18}O regions on an expanded scale. The observed mass resolution ranges from 0.13 amu for He to 0.23 amu for O. There are 1020 He, 2031 C, 244 N, and 3142 O events in the histograms. The number of He nuclei analyzed by HIST was $< 1\%$ of its actual abundance in this flare (see Table 2) because the instrument's logic is designed to favor the analysis of $Z > 2$ nuclei (Althouse *et al.* 1978).

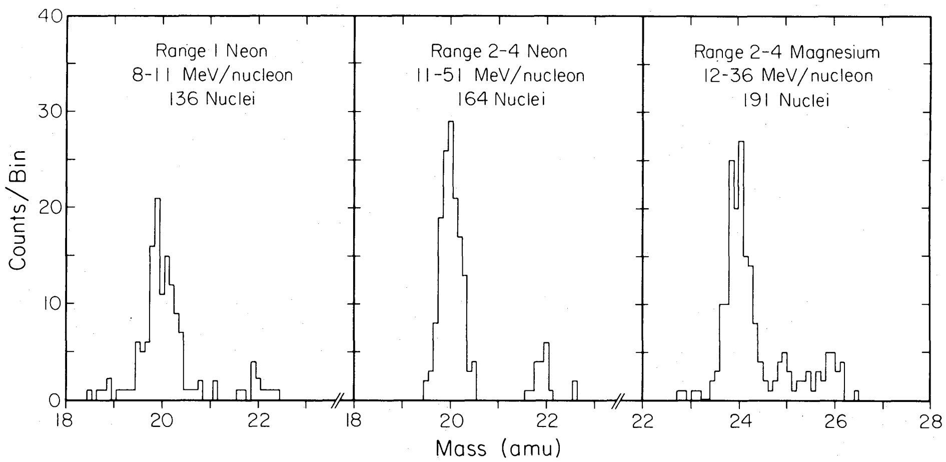

FIG. 3.—Mass histograms for solar flare Ne and Mg isotopes. The Ne data are shown in two energy intervals.

what the event selection criteria. Overall, we have more than doubled our sample of solar flare Ne nuclei.

Although the range 1 mass resolution for Ne (0.27 amu) is not expected to be as good as at higher energy (0.20 amu), there is a well-defined ^{22}Ne peak. The few events near ^{21}Ne may include one or two real ^{21}Ne events, but may also be spillover from ^{20}Ne or ^{22}Ne, and therefore only an upper limit for the ^{21}Ne abundance is possible. The background events visible on the low-mass side of range 1 ^{20}Ne are due to nuclei that pass between the strips of M1 and M2, where there are known to be regions of incomplete charge collection. There is also a corresponding background visible on the low-mass side of ^{12}C, ^{14}N, and ^{16}O (see Fig. 2). Note that this background mechanism, as well as others that introduce signal loss in the energy measurements (e.g., nuclear interactions) always leads to an underestimate of the particle's true mass. Thus, for example, we expect the background at ^{11}C to be greater than that at ^{13}C due to such effects.

Table 1 summarizes our results for 11 different isotope abundance ratios, including a re-analysis of our Mg data, which differs from our earlier results (Mewaldt *et al.* 1981*a*) only in the third significant figure. Our improved ^{22}Ne/^{20}Ne ratio is somewhat smaller, but consistent with our earlier value of 0.13 ($+0.04$, -0.03). The uncertainties in Table 1 include both statistical uncertainties, computed using the maximum likelihood method, and upper limits on systematic uncertainties, due to possible background at the location of the rare neutron-rich isotopes (Spalding 1982).

Because HIST selects events for analysis on the basis of their range in the telescope, each isotope of a given element has a slightly different acceptance window in terms of energy per nucleon. We corrected for this difference using the observed energy spectra for each element, with the conventional assumption that the isotopic abundances are independent of energy per nucleon, or equivalently, either velocity or momentum per nucleon. It is also possible that the abundances are independent of some other variable, as discussed in the Appendix. If, for example, that variable is rigidity, the necessary corrections are in the opposite sense and several times greater in magnitude. Although the available data support the conventional approach to making this correction, it will be important to reexamine this question when more data become available.

Figure 4 shows selected isotopic ratios as a function of energy per nucleon. Although it is possible that SEP isotopic abundances vary with energy (see, e.g., the suggestion by Black 1983), there is no obvious trend to the data in Figure 4. In Figure 5, these same three isotopic ratios are shown as a function of time over the course of the solar event. Von Rosenvinge and Reames (1979) found that the elemental composition (e.g., the Fe/O ratio) did vary during the first 36 hours of this event, especially at low energies (<5 MeV

TABLE 1

ISOTOPE RATIOS: 1978 SEPTEMBER 23 SOLAR FLARE

Isotope Ratio	Energy (MeV per nucleon)	Observed Ratio[a]	Solar System (Cameron 1982)
^{3}He/^{4}He	5–32	<0.0026	...
^{13}C/^{12}C	6–39	$0.0095^{+0.0042}_{-0.0029}$	0.0111
^{14}C/^{12}C	6–39	<0.0014	radioactive
^{15}N/^{14}N	9–42	$0.008^{+0.010}_{-0.005}$	0.0037
^{17}O/^{16}O	7–45	<0.0021	0.00037
^{18}O/^{16}O	7–45	$0.0015^{+0.0011}_{-0.0007}$	0.00204
^{21}Ne/^{20}Ne	11–51	<0.014	0.0030
^{22}Ne/^{20}Ne	8–51	$0.109^{+0.026}_{-0.019}$	0.122
^{25}Mg/^{24}Mg	12–36	$0.148^{+0.046}_{-0.026}$	0.129
^{26}Mg/^{24}Mg	12–36	$0.148^{+0.043}_{-0.025}$	0.142
$^{25+26}$Mg/^{24}Mg	12–36	$0.296^{+0.063}_{-0.038}$	0.271

[a] 68% confidence intervals or 84% confidence limits.

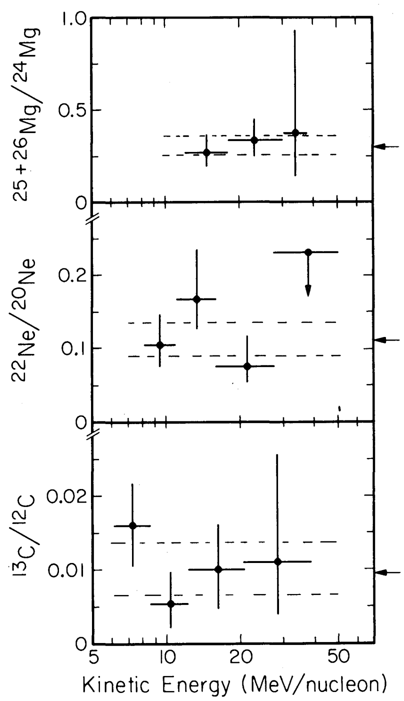

FIG. 4.—Observed isotopic abundance ratios as a function of energy per nucleon. The arrows indicate the mean values, while the dashed lines show the 84% confidence limits.

per nucleon). Such composition variations are often observed during the early part of solar flares (see, e.g., Mason, Gloeckler, and Hovestadt 1983). There is, however, no significant evidence in Figure 5 for any time dependence to the isotopic composition.

In order to determine the elemental composition of nuclei observed in this event, daily average energy spectra from ~5 to ~40 MeV per nucleon were computed for eight abundant elements from He to Fe. The spectra of C, N, O, Ne, Mg, and Si were all found to be consistent with a common spectral shape, as shown in Figure 6. Over most of the observable energy range this common shape was found to be reasonably well represented by an exponential in momentum per nucleon (p). Thus, $dJ/dp \propto \exp(-p/p_0)$, where p_0 was typically ~20 (MeV/c) per nucleon. Although the Fe data could not be fit by this spectral form, it is not unusual for the Fe spectrum to differ from those of lighter elements (see, e.g., Cook, Stone, and Vogt 1980).

Table 2 shows the relative element abundances summed over the days 1978 September 25 to September 28. Following Cook, Stone, and Vogt (1980), we have excluded data from the onset of the flare in determining the elemental composition because some of the abundances were changing with time (von Rosenvinge and Reames 1979; Spalding 1982). Figure 7 compares our results with other measurements from this same event, and with the average SEP composition determined from *Voyager* data by Cook, Stone, and Vogt (1980, 1984). Overall, the three measurements of the 1978 September 23 event are seen

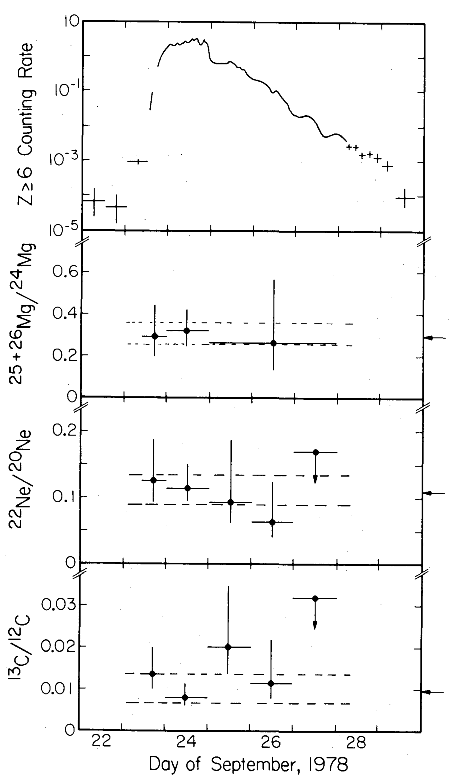

FIG. 5

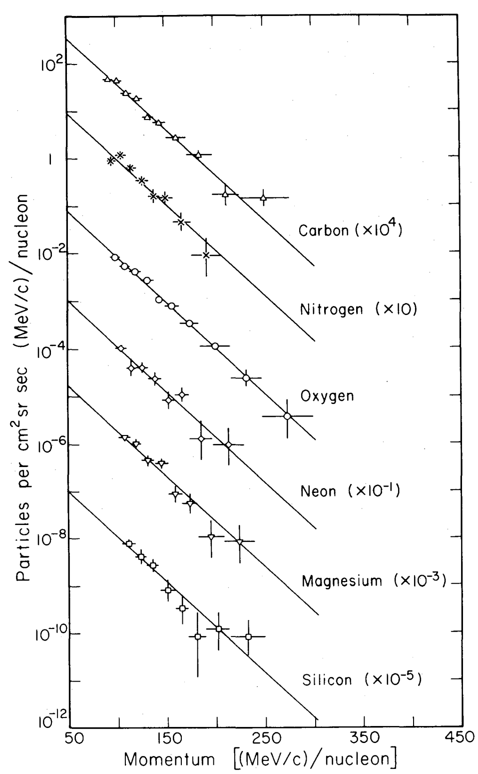

FIG. 6

FIG. 5.—Observed isotopic abundance ratios as a function of time. The top panel shows the count rate of $Z \geq 6$ nuclei with ≥ 5 MeV per nucleon. The arrows and dashed lines indicate the mean value and 84% confidence limits.

FIG. 6.—Momentum spectra for six elements, derived from 1978 September 25 data. The straight lines through the data all have the same slope [$p_0 = 22.4$ (MeV/c) per nucleon] and result from a simultaneous fit to all six elements. For plotting purposes the data for the individual elements have been multiplied by the scale factors shown.

TABLE 2

ELEMENT COMPOSITION: 1978 SEPTEMBER 23 SOLAR FLARE EVENT[a]

Element	Abundance Relative to Oxygen
He	53 ± 2[b]
C	0.47 ± 0.03
N	0.13 ± 0.01
O	1.0
Ne	0.13 ± 0.01
Mg	0.20 ± 0.02
Si	0.13 ± 0.02
Fe	0.08 ± 0.02[c]

[a] For the time period 1978 September 25–28. Energy range is ~5–50 MeV per nucleon.

[b] For 1978 September 26–29.

[c] Energy-dependent; value given is for 8–24 MeV per nucleon.

to be in reasonable agreement. The differences at He and Ne appear to be due in part to differences in the time periods over which the measurements were taken (see Spalding 1982). Although it is apparent that (when normalized to O) this flare is somewhat depleted in elements with $16 \leq Z \leq 26$ relative to the *Voyager* composition, the Fe/O ratio for this event is well within the range of values that is typical of large solar events (see, e.g., McGuire, von Rosenvinge, and McDonald 1979; Cook, Stone, and Vogt 1980; Meyer 1981*a*, *b*). Similarly, the Ne/O ratio that we find (0.13 ± 0.01; see Table 2) is lower than the average value found by the *Voyager* study, but well within the range of values found for other large flares. Note also that the Ne/Si ratio that we determine agrees exactly with the SEP average from *Voyager*, and thus it does not appear that the Ne elemental abundance is unusual in this event. If the HIST abundances in Table 2 are compared with the *Voyager* results for flares having approximately the same Fe/O ratio (Cook, Stone, and Vogt 1980), the agreement is excellent for all eight elements. We conclude that there is no evidence from either the energy spectra or the elemental composition that would suggest that this event should have an unusual isotopic composition.

IV. COMPARISON WITH OTHER SAMPLES OF SOLAR SYSTEM MATERIAL

Almost all of our present knowledge about the isotopic composition of material in the solar system (and, indeed, about material in our Galaxy) is based on measurements of terrestrial and meteoritic samples. Two recent tabulations of such "solar system abundances" include one by Cameron (1982) and another by Anders and Ebihara (1982). Although little is known about the extent to which such compilations are representative of the composition of the Sun, they serve as a useful standard against which to compare our measurements.

In Figure 8 we compare our SEP results with Cameron's solar system tabulation, with solar wind measurements, and with other SEP measurements. These measurements are also summarized in Table 3, along with other data. Note that while our results are in all cases consistent with Cameron's tabulation, there is a significant difference between the two SEP measurements of $^{22}Ne/^{20}Ne$ and that from the SW, as first noted by Dietrich and Simpson (1979) and Mewaldt *et al.* (1979). A maximum likelihood calculation indicates that there is less than a 3% probability that our observations are consistent with a $^{22}Ne/^{20}Ne$ ratio as small as that of the solar wind. Cameron's $^{22}Ne/^{20}Ne$ value is based on the meteoritic component "neon-A" found in carbonaceous chondrites (Pepin 1967). Anders and Ebihara, on the other hand, chose the SW $^{22}Ne/^{20}Ne$ value for their tabulation.

Figure 9 shows selected solar system measurements of $^{22}Ne/^{20}Ne$ on an expanded scale. The major neon components in meteorites are neon-A and neon-B, the latter generally accepted to be due to directly implanted solar wind (see, e.g., the review by Podosek 1978). Of special relevance here is neon-C, which has been identified as SEP neon that has been directly implanted in lunar and meteoritic material (Black 1972). It is interesting that all of the recent attempts to measure this component (Etique, Signer, and Wieler 1981; Yaniv and Marti 1981; Venkatesan, Nautiyal, and Rao 1981; Wieler, Etique, and Signer 1982; Venkatesan *et al.* 1983) find a $^{22}Ne/^{20}Ne$ ratio greater than that of present day SW Ne, and with one possible exception (Venkatesan, Nautiyal, and Rao 1981), greater than that of neon-B, thought to represent implanted SW. In a recent review of these measurements, Black (1983) concludes that neon-C has a $^{22}Ne/^{20}Ne$ ratio of 0.090–0.097. Note that neither of the two satellite measurements could be considered inconsistent with this range.

From a comparison of the satellite measurements with those of neon-C (which are interpreted to represent SEP neon with ≥ 1 MeV per nucleon), Black (1983) suggested that there might be an energy dependence to the SEP $^{22}Ne/^{20}Ne$ ratio. Although the suggested energy dependence is consistent with the available data, it is not clear that it is required, given the present uncertainties in the observations.

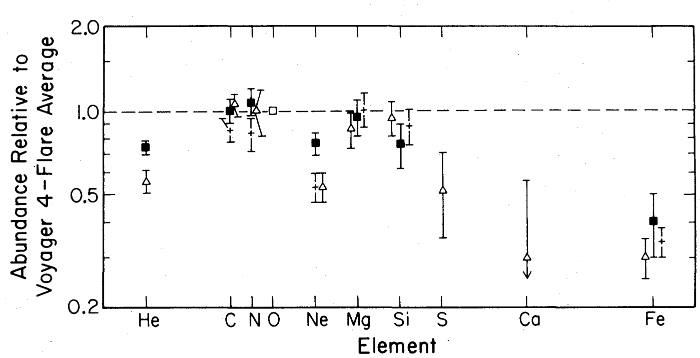

FIG. 7.—Elemental abundances measured in the 1978 September 23 flare divided by the average SEP abundances determined on *Voyager 1* and *2* by Cook, Stone, and Vogt (1980). Data points (all normalized to oxygen): ■ this work, 10:00 UT September 25 to 23:59 UT September 28; + von Rosenvinge and Reames (1981), September 24; △ McGuire, von Rosenvinge, and McDonald (1979), 20:00 UT September 23 to 23:59 UT September 26.

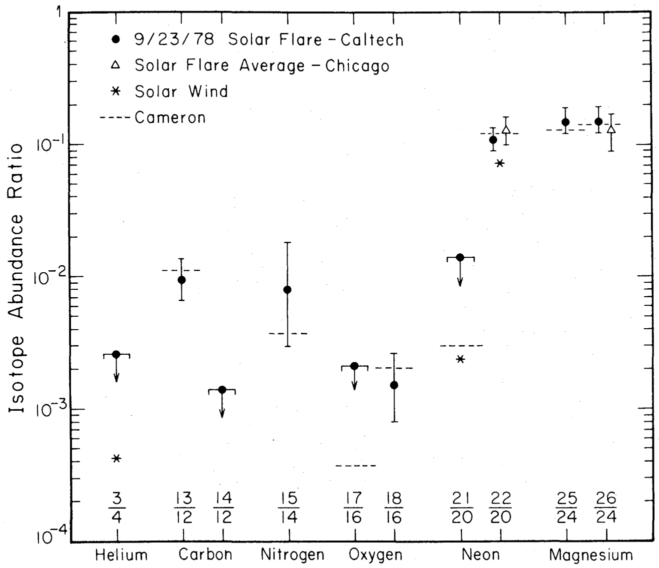

FIG. 8

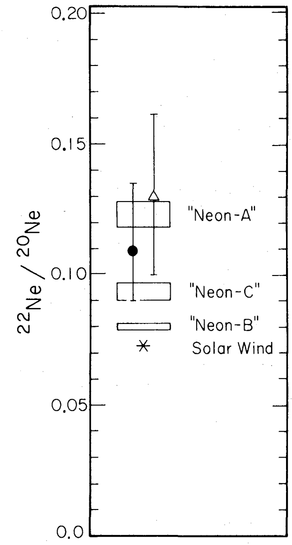

FIG. 9

FIG. 8.—Comparisons of isotopic abundances measured for solar nuclei and for the solar wind, with the solar system abundances tabulated by Cameron (1982). References to the data points: ● this work, Table 1; △ Dietrich and Simpson (1979, 1981), ✳ Geiss *et al.* (1972).

FIG. 9.—Comparison of selected solar system $^{22}Ne/^{20}Ne$ ratios. SEP measurements: ● this work; △ Dietrich and Simpson (1979). Solar wind: ✳ Geiss *et al.* (1972). Neon-A and B are meteoritic components recently reviewed by Podosek (1978). Neon-C is thought to represent SEP neon implanted in lunar and meteoritic material (Black 1983).

TABLE 3

ISOTOPIC ABUNDANCE MEASUREMENTS

Element	Isotope Ratio	Value	Source	Reference
He	$^3He/^4He$	$4 \pm 2 \times 10^{-4}$	Solar spectra	Hall 1975
		$4.3 \pm 0.2 \times 10^{-4}$	Average solar wind	Geiss *et al.* 1972
		$<2.6 \times 10^{-3}$	Solar energetic particles	This work
C	$^{13}C/^{12}C$	0.0111	Terrestrial	Holden 1980
		0.0104 ± 0.0011	Solar spectra	Hall 1973
		0.0109–0.0113	Solar wind implanted in lunar soils	Becker 1980
		$0.0095^{+0.0042}_{-0.0029}$	Solar energetic particles	This work
N	$^{15}N/^{14}N$	0.0037	Terrestrial air	Holden 1980
		0.0034–0.0043	Meteoritic	Geiss and Bochsler 1982
		0.0031–0.0041	Solar wind implanted in lunar soils	Becker 1980
		$0.008^{+0.010}_{-0.005}$	Solar energetic particles	This work
O	$^{17}O/^{16}O$	0.00037	Terrestrial air	Holden 1980
		<0.0021	Solar energetic particles	This work
	$^{18}O/^{16}O$	0.00204	Terrestrial air	Holden 1980
		0.0021 ± 0.0007	Solar spectra	Hall 1973
		$0.0015^{+0.0011}_{-0.0007}$	Solar energetic particles	This work
Ne	$^{21}Ne/^{20}Ne$	0.0026 ± 0.0001	Neon-B	Black 1972
		0.0024 ± 0.0003	Solar wind	Geiss *et al.* 1972
		<0.014	Solar energetic particles	This work
	$^{22}Ne/^{20}Ne$	0.122 ± 0.006	Neon-A	Pepin 1967
		0.080 ± 0.001	Neon-B	Black 1972
		0.078 ± 0.002	Solar wind implanted in lunar soils	Eberhardt *et al.* 1972
		0.073 ± 0.001	Solar wind	Geiss *et al.* 1972
		0.090–0.097	Neon-C	Black 1983
		0.13 ± 0.03	Solar energetic particles	Dietrich and Simpson 1979
		$0.13^{+0.04}_{-0.03}$	Solar energetic particles	Mewaldt *et al.* 1979
		$0.109^{+0.026}_{-0.019}$	Solar energetic particles	This work
Mg	$^{25}Mg/^{24}Mg$	0.129	Terrestrial	Holden 1980
		0.125 ± 0.038	Solar spectra	Boyer *et al.* 1971
		Terrestrial $\pm$ 20%	Solar wind implanted in lunar soils	Zinner *et al.* 1977; E. Zinner 1979, private communication
		$0.14^{+0.05}_{-0.02}$	Solar energetic particles	Mewaldt *et al.* 1981*a*
		$0.148^{+0.046}_{-0.026}$	Solar energetic particles	This work
	$^{26}Mg/^{24}Mg$	0.142	Terrestrial	Holden 1980
		0.125 ± 0.038	Solar spectra	Boyer *et al.* 1971
		Terrestrial $\pm$ 20%	Solar wind implanted in lunar soils	Zinner *et al.* 1977; E. Zinner 1979, private communication
		$0.15^{+0.04}_{-0.03}$	Solar energetic particles	Mewaldt *et al.* 1981*a*
		0.13 ± 0.04	Solar energetic particles	Dietrich and Simpson 1981
		$0.148^{+0.043}_{-0.025}$	Solar energetic particles	This work

Although neon is perhaps a unique element, with its diverse range of solar system isotopic compositions, recent lunar and meteoritic measurements have also discovered isotopic "anomalies" in the other elements under study here. Except for possibly He, the magnitude of the observed isotopic variations for these other elements is much smaller, ranging from $<5\%$ for C, O, and Mg, to $\sim 20\%$ for N (see, e.g., the reviews by Podosek 1978, Clayton 1978, and Lee 1979). Unfortunately our SEP measurements are not as yet precise enough to allow a meaningful comparison with these isotopic variations analogous to that for Ne. However, for C, O, and Mg, the general agreement between our SEP values, the limited spectroscopic data available (see Table 3), and the Cameron abundances suggests that the solar isotopic composition of these elements does not differ greatly from that typical of terrestrial and meteoritic material.

V. DISCUSSION

There are now two independent approaches that find a difference between the isotopic composition of SEP neon and SW neon. The question remains as to how the Sun can apparently emit two distinct isotopic components, and which, if either, represents the composition of the Sun. A number of possible explanations have already been considered. Mewaldt *et al.* (1979) considered the possibility that SEP ^{22}Ne might include substantial spallation contributions arising from the passage of flare particles through the solar atmosphere. However, they concluded that the prompt production of ^{21}Ne should be considerably greater than that of ^{22}Ne and thus the absence of any observed ^{21}Ne implied that there was negligible ^{22}Ne production at the time of the flare.

Although there are significant flare-to-flare variations in the elemental composition of SEPs, there is no evidence of any dependence of the ^{22}Ne/^{20}Ne ratio on the Fe/O ratio, over the range from Fe/O ≈ 0.08 to Fe/O ≈ 1 (Dietrich and Simpson 1979; Mewaldt 1980; Spalding 1982). However, the statistical uncertainties in the ^{22}Ne/^{20}Ne measurements are large, and flare-to-flare variations in ^{22}Ne/^{20}Ne of a factor of ~ 2 cannot presently be ruled out.

Another possibility is mass-dependent fractionation in either the SEP or SW acceleration or propagation processes. To perform a simple test of this possibility with our SEP data, we consider a "normalized abundance ratio," defined to be the SEP isotope abundance ratio divided by the corresponding "solar system" abundance ratio from Cameron (1982), which, for these purposes, we assume represents the isotopic composition of solar C, O, and Mg. Figure 10 shows this normalized abundance ratio for five pairs of isotopes, where for ^{22}Ne/^{20}Ne we consider the possibility of both neon-A and SW neon as a standard. A simple possibility for mass fractionation during the solar flare acceleration or propagation processes would be a linear fractionation law, with the change in the abundance ratio for two isotopes of the same element proportional to the ratio of their masses. If $F(j, i)$ is the enhancement of isotope j relative to isotope i, and α is the constant of proportionality, then $F(j, i) = \alpha[(A_j/A_i) - 1]$. Fitting this to the four reduced ratios for the C, O, and Mg isotopes we find $\alpha = 0.3 \pm 1.7$, a result consistent with $\alpha = 0$. Thus under the above assumptions, our C, O, and Mg data are consistent with the absence of fractionation. The value of α found above predicts only a small change for the reduced ^{22}Ne/^{20}Ne abundance ratio of $F(22, 20) = 0.03 \pm 0.17$. This change is consistent with our observed ratio if neon-A (or neon-C) is used as the standard

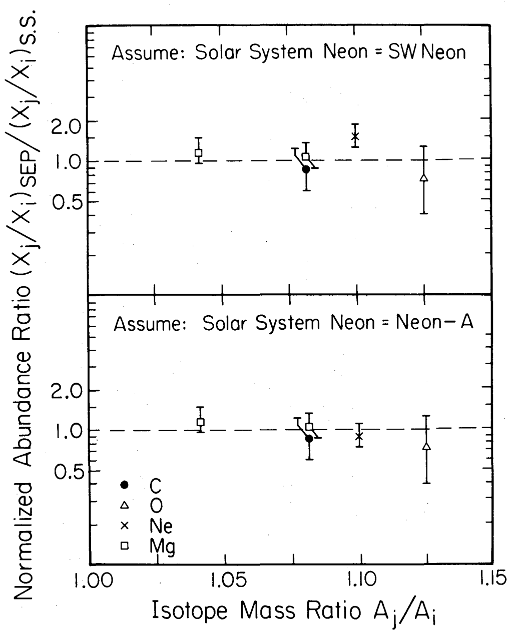

FIG. 10.—Plots of the "normalized abundance ratio" (SEP value divided by Cameron's "solar system" value) vs. the isotope mass ratio for five pairs of isotopes. Two possible assumptions for "solar system" neon are shown.

(Fig. 10*a*). If, however, SW neon is used as the standard, our observation is inconsistent with the predicted ratio at the $\sim 94\%$ confidence level. Thus, within the limits of the stated assumptions, the ensemble of our isotope results favor a solar isotope composition that is significantly more enriched in ^{22}Ne than is the solar wind.

It is also possible that the SW has undergone mass dependent fractionation. While there are direct SW isotopic measurements for only He, Ne, and Ar (Geiss *et al.* 1972), there are also indirect measurements of solar wind implanted in the lunar soil that indicate anomalies in the C and N isotopic abundances (see, e.g., Kerridge *et al.* 1977; Becker 1980). Although little is known about the solar wind isotopic composition, it does not appear that the SW has been significantly altered by a simple, linear mass-dependent fractionation process of the type considered above (Spalding 1982). Geiss (1982) has recently considered processes that might lead to the fractionation of SW *elemental* abundances but does not expect large isotopic effects from these models.

There is also the possibility of selective isotope enhancements. For example, there is a class of (usually small) SEP events which are termed "^{3}He-rich" because the ^{3}He/^{4}He ratio is as large as 0.1 to 1, orders of magnitude greater than the average solar wind value of $\sim 4 \times 10^{-4}$ (see the review by Ramaty *et al.* 1980). It has also been found that the solar wind ^{3}He/^{4}He ratio varies by more than a factor of 10 on time scales of the order of hours to days (Ogilvie *et al.* 1980). One of the theoretical models for ^{3}He-rich events (Fisk 1978), thought to apply only to small flares, would also be expected to enhance certain heavier elements (Mason *et al.* 1980). It is not clear, however, whether this model could produce isolated enhancements of individual heavy isotopes such as ^{22}Ne. Furthermore, we do not find either a ^{3}He enhancement or an anomalous elemental composition in the 1978 September 23 flare (our ^{3}He/^{4}He upper limit appears to be the lowest yet reported for a single solar event), suggesting that the conditions necessary for this model do not apply to this large flare event.

In another, more recent model for ^{3}He-rich events, Hayakawa (1983) suggests that radiation pressure from He Lyα can preferentially heat ^{3}He in cool regions of the corona so that it may be subject to preferential acceleration in SEP events. This mechanism works only for rare neutron-poor isotopes such as ^{3}He; it does not enhance neutron-rich isotopes such as ^{22}Ne.

Mullan (1983) has proposed a pre-acceleration model for solar flares that, on the average, would be expected to enhance the ^{22}Ne/^{20}Ne ratio more than other isotopic ratios. A test of this model, not yet possible with the present data, would be correlated enhancements of ^{22}Ne/^{20}Ne and ^{13}C/^{12}C.

It appears that comprehensive measurements of a number of isotopic ratios in both the SW and in a number of SEP events are required to establish the systematics of any fractionation of either the SW or SEP isotopic composition relative to that of the Sun. Among the other measurements that might shed light on the puzzle of solar system ^{22}Ne would be a determination of ^{22}Ne/^{20}Ne in the Jovian atmosphere (which may be possible on the *Galileo* mission scheduled for launch in 1986), since this is thought to represent a sample of the primitive solar nebula.

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APPENDIX

CORRECTIONS FOR RANGE-SAMPLING AND SPECTRAL EFFECTS

HIST (and many similar instruments) selects energetic nuclei for analysis on the basis of their range in a stack of detectors, and as a result, a slightly different energy per nucleon interval is sampled for each isotope. In this Appendix we discuss the corrections that are required for this sampling effect, and their dependence on the nature of solar flare energy spectra.

To illustrate the effect of selection by range, the range-energy relation can be approximated by a power law: $R(Z, A, T) \propto (A/Z^2)T^b$, where T is kinetic energy per nucleon and $b \approx 1.7$ for $5 \leq T \leq 50$ MeV per nucleon. Two isotopes of the same element (with masses $A_2 > A_1$) which stop in a thickness R_0, have energies per nucleon related by $(T_2/T_1) = (A_1/A_2)^{1/b}$. Thus, the heavier isotope (A_2) requires less energy per nucleon to traverse the same range and will be favored for typical solar-flare energy spectra. It would be a straightforward matter to correct for this observational bias if the energy spectra of both isotopes were accurately known. However, in the present instance there is sufficiently accurate data for only the dominant isotope of each element (see Figs. 4 and 6), and it is therefore necessary to assume that the rare isotopes have a similar spectral shape.

In this study, we have made the conventional assumption that the isotopic abundances are independent of energy per nucleon (or, equivalently, either velocity, or momentum per nucleon), an assumption that is consistent with both the isotopic ratios in Figure 4, and the *element* spectra in Figure 6. However, it is possible that with improved statistical accuracy it would be found that some other physical parameter (e.g., rigidity) better organizes the spectra of the various species. We consider the effects of this possibility below.

We assume that the isotopic abundances are independent of some physical parameter S, which we label the "relevant spectral parameter," and that the spectra are given by

$$\frac{dJ}{dS} = K_i\, f(S)\,,$$

such that the abundance ratio of two isotopes (A_j heavier than A_i) is given by K_j/K_i. The correction factor C_{ji} that relates the observed abundances N_j/N_i to the actual abundance ratio is obtained by integrating the observed spectra over the range limits sampled. Thus,

$$C_{ji} = \frac{K_j}{K_i}\left(\frac{N_i}{N_j}\right) = \frac{\int_{S_i(R_1)}^{S_i(R_2)} f(S)dS}{\int_{S_j(R_1)}^{S_j(R_2)} f(S)dS}\,.$$

Table 4 lists some of the possible choices for the relevant spectral parameter S. Also shown in each case is the magnitude of the correction factor $C_{22,20}$ that results from integrating our measured Ne spectrum over range 1 to range 4 in HIST. The isotopic results in Tables 1 and 2 include the correction appropriate for T, v, or p. Note that the magnitude of the correction for other possible choices of S is sufficiently different to have a significant effect on our results.

As indicated in Table 4, it is possible to eliminate some of the possible choices for the relevant spectral parameter using the observed *element* spectra (see Fig. 6). Thus, for either total kinetic energy ($S = E$) or total momentum ($S = P$), we would expect the spectra in Figure 6 to all have differing slopes, with, for example, a Si/O ratio that varies by more than a factor of 10 as a function of momentum per nucleon.

The quantities total kinetic energy per charge (E/q) and rigidity (P/q) depend on the charge state of solar flare nuclei. The observed element spectra are consistent with either of these two choices for the relevant spectral parameter if the elements C to Si are essentially fully stripped (mass to charge ratios of $A/q = 2$), but not if elements such as Mg and Si retain several electrons. Several pieces of evidence suggest that SEP nuclei are *not* all fully stripped in our energy interval.

At somewhat lower energies, from 0.3 to 2.4 MeV per nucleon, direct measurements of the charge states of He, C, O, and Fe are available for the 23 September 1978 event from Gloeckler *et al.* (1981). They report A/q values for C, O, and Fe of 2.1, 2.2, and 4.1; similar values are obtained for nine other large solar flare events. These results are consistent with a coronal temperature of $\sim$(1–2) $\times 10^6$ K, and suggest that the corresponding A/q values for Mg and Si would be $\sim$2.8 (based on Jordan 1969). If these

TABLE 4

POSSIBLE "RELEVANT SPECTRAL PARAMETERS"

Quantity	Definition	Comments	$C_{22,20}$
T	Kinetic energy per nucleon	Used in this paper; Consistent with element spectra	0.87
v	velocity		
p	momentum per nucleon		
E	total kinetic energy	Inconsistent with element spectra	1.15
E/q	energy per charge	Consistent with element spectra only if nuclei essentially fully ionized.	
P	total momentum	Inconsistent with element spectra	1.40
P/q	rigidity	Consistent with element spectra only if nuclei essentially fully ionized.	

NOTE.—$C_{22,20}$ is the correction factor to convert the observed ^{22}Ne/^{20}Ne ratio to the actual abundance ratio (evaluated for the Ne spectrum observed in the 1978 September 23 solar event).

TABLE 5

COMPARISON OF THE EFFECT OF DIFFERENT SPECTRAL CORRECTIONS

		CORRECTED FOR KINETIC ENERGY PER NUCLEON SPECTRA		CORRECTED FOR RIGIDITY SPECTRA	
ISOTOPE RATIO	CAMERON 1982	Corrected Value	Normalized Abundance Ratio[a]	Corrected Value	Normalized Abundance Ratio[a]
^{13}C/^{12}C	0.0111	$0.0095^{+0.0042}_{-0.0029}$	$0.86^{+0.37}_{-0.27}$	$0.0132^{+0.0058}_{-0.0040}$	$1.19^{+0.52}_{-0.36}$
^{15}N/^{14}N	0.0037	$0.008^{+0.010}_{-0.005}$	$2.2^{+2.7}_{-1.4}$	$0.010^{+0.014}_{-0.005}$	$2.7^{+3.8}_{-1.4}$
^{18}O/^{16}O	0.00204	$0.0015^{+0.0011}_{-0.0007}$	$0.74^{+0.54}_{-0.35}$	$0.0025^{+0.0019}_{-0.0012}$	$1.2^{+0.9}_{-0.6}$
^{22}Ne/^{20}Ne	0.122	$0.109^{+0.026}_{-0.019}$	$0.89^{+0.22}_{-0.15}$	$0.175^{+0.043}_{-0.030}$	$1.43^{+0.35}_{-0.24}$
^{25}Mg/^{24}Mg	0.129	$0.148^{+0.046}_{-0.026}$	$1.15^{+0.35}_{-0.20}$	$0.192^{+0.060}_{-0.034}$	$1.49^{+0.46}_{-0.26}$
^{26}Mg/^{24}Mg	0.142	$0.148^{+0.043}_{-0.025}$	$1.04^{+0.30}_{-0.17}$	$0.249^{+0.073}_{-0.042}$	$1.75^{+0.52}_{-0.29}$

[a] Normalized to the Cameron 1982 values.

charge states are also appropriate to our energy interval, it can be argued that neither E/q nor P/q can be the relevant spectral parameter, since either of these would result in a significant (approximately a factor of 3) dependence of, e.g., the Mg/O and Si/O ratios on momentum per nucleon (Fig. 6). There is also indirect evidence that suggests that the heavy nuclei observed in large solar flares are not fully stripped. It is commonly observed that elemental abundance ratios such as Fe/O and O/He vary with time during the early phase of solar flare events, at both $\sim$1 MeV per nucleon (Mason, Gloeckler, and Hovestadt 1983) and at $\sim$10 MeV per nucleon (Cook 1980). These variations have been interpreted as a result of rigidity dependent propagation, leading to indirect A/q estimates at $\sim$1 MeV per nucleon of $\sim$3 for C and O, and $\sim$6 for Fe (Mason, Gloeckler, and Hovestadt 1983).

Note in Table 4 that if rigidity (P/q) were to be the relevant spectral parameter, the magnitude of the required spectral corrections is several times larger and in the opposite sense than for either T, v, or p. Table 5 compares the isotopic abundances obtained using kinetic energy as the relevant spectral parameter with those using rigidity. Note that the rigidity correction increases the magnitude of the difference between the SEP ^{22}Ne/^{20}Ne ratio in the solar wind ($=0.073$) and in SEPs (and, indeed, none of the other choices considered in Table 4 leads to better agreement than T). Note also that for the other measured isotopic ratios the rigidity correction also results in poorer overall agreement with the solar system abundances of Cameron (1982). It should perhaps be pointed out that the absolute magnitudes of the correction factors C_{ji} depend on the "spectral slope" and thus vary with the spectra of individual flares. However, the *relative* magnitudes of the various C_{ji}, and their sense (greater than or less than 1), depend only on the relative spectral parameter.

Thus, while the available data favor the conventional approach adopted here, the proper method to account for this sampling effect remains an open question which needs to be investigated further when SEP isotope measurements with better statistical accuracy become available.

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